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Electromagnetic Induction Prediction of Soil Salinity by Extrapolated Calibration Model in M'Sila (Algeria)

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ABSTRACT

The main objective of this paper is to evaluate the *in situ* estimation of salinity by using the external calibration equations (*ex situ*) between the electrical conductivity measured laboratory (ECm) and the apparent electrical conductivity (ECa) measured by EM38. Results showed that EM38 data from apparent soil electrical conductivity are highly correlated with salinity. The experiment was conducted on four sandy soils A, B, C and D located at M'Sila (Algeria). Calibration equations for converting ECa into electrical conductivity calculated (ECc) were derived using the simple linear regression (SLR) (ECm = f (ECa)). The results show that the average deviation between ECm (*in situ*) and ECc of site A calculated by B, D and G equations of the SLR model (*ex situ*) are low (0.32 dS/m and 0.66 dS/m) except for site C. Moreover, except the map C, maps B, D and G of site A realized by SLR model (*ex situ*) differ slightly from map A carried out by SLR (*in situ*), hence the significance of this approach, which can be generalized to wider areas provided the pedological context is fairly homogeneous.

INTRODUCTION

Electromagnetic conductivity is widely used for mapping and temporal monitoring of soil salinity, especially in large agricultural areas (De Jong et al. 1979, Rhoades 1992, Jung et al. 2006, Urdanoz & Aragüés 2011). The success of this method is due to the fact that it offers a larger data set and higher density measurements than the conventional method which relies on the saturated paste extract. Generally used in relative values, electromagnetic measurements can be calibrated against the soil solution extraction methods and measures of the electrical conductivity (EC) in laboratory (Corwin & Rhoades 1984, McKenzie et al. 1989). However, the quality of the salinity levels estimated from the readings of the electromagnetic conductivity is highly dependent on calibration equations that relate the EC of soil samples with apparent electrical conductivities (ECa) (Triantafilis et al. 2000). So, many calibration models from ECa to EC were used (Rhoades & Corwin 1981, McKenzie et al. 1989). In this sense, López-Bruna & Herrero (1996) have shown that simple linear models generally yield sufficiently accurate results. However, the use of these models requires the studied parameter to be more dominant compared to other soil parameters (Cook et al. 1989, Sudduth et al. 2005, Viscarra et al. 2011, Kuang et al. 2012). However, other studies have relied on nonlinear models to minimize the EC estimation errors. So, it turns out that getting a good calibration depends on the vertical and spatial homogeneity of soil parameters of the studied soils. Traditionally, the calibration equations ECa to EC are carried out within the site or parcel mapping. These equations, which are realized from a relatively small number of measurements, performed in punctual places of coordinates Xn and Yn (n = number of points used for calibration of ECa to EC), will be used to predict EC in any other location of the studied area. The main objective of this study is to evaluate the quality of *in situ* estimation salinity by using the *ex situ* calibration equations between the EC measured in laboratory (ECm) and the apparent EC (ECa) measured by EM38. This will evaluate the possibility to generalize the calibration equations conducted in a restricted area to a much wider one.

MATERIALS AND METHODS

Study area: The study area is located south of the Chott El Hodna in M'Sila, Algeria bounded by longitudes 4°31' to 4°35' East and latitudes 35°20' to 35°22' North (Fig. 1). It is characterized by a vast sandy area colonized by a combination of psammophile and halophytes plant, when soils are not cultivated. Soils are Typic Haplosalid (Soil Survey Staff, 1999). The climate is arid (167 mm rain/year), temperate in winter with very strong potential evapotranspiration (1300 mm/year). This region is dominated by traditional irrigated agriculture practiced on small plots that do not exceed a few dozen acres and are cultivated differently. The most dominant agricultural practices are the vegetable crops and fruit trees. Most of the crops are irrigated by flood, the drip irrigation is practiced on some plots. This diversity of cultures generates different periods of land use and therefore different water supplies in space and time, even within the same plot. The salinity gradient is south-north direction and follows the general direction of the slope, which is low (<2%). The drainage water flows into the saline depression (sebkha), located north of the area.

Method of study: The experiment was carried out on 4 sites (A, B, C and D) representative of agricultural practices in the studied area. Site A is located on soils sporadically cultivated with vegetable crops and irrigated by flood. Site B includes vegetable crops and arboriculture regularly irrigated by flood. Site C is a young tree planting irrigated by a drip system. Site D is fallow for several years. In each site, ECa measurements were taken with an electromagnetic conductivity meter (EM38 Geonics Ltd., Canada) in the vertical mode (EM_V), according to the south-north oriented transects, corresponding to salinity upward gradient. This allowed direct measurement of apparent electrical conductivity (ECa) to a depth of 150 cm. In total, 41 measurements were performed including 13 on site A, 7 on site B, 10 on site C and 11 on site D.

In parallel, at each point of ECa measurement, soil samples were collected by auger in increments of 30 cm to a depth of 150 cm for laboratory analysis. The particle size fractions, total $CaCO_3$ and gypsum rates, the $pH_{water\ (2/5)}$, the water content (H%) and electrical conductivity measured ($ECm_{(1/5)}$) were determined for each soil layer and weighted for the 150 cm depth. Thus, it becomes possible to establish the relationship between ECa and ECm assuming for each studied site, an equation ECm=f (ECa). These equations are called equations A, B, C, D and G respectively for measurements in the sites A, B, C and D. The equation G is obtained by considering all of the measurements in the sites B, C and D. To do this, three equation models were developed to predict ECm. The used model is based on simple linear regression equations (SLR) and considers that only the ECm factor is responsible for the change in ECa (De Jong et al. 1979, Job 1987, Herrero et al. 2003, Feikema & Baker 2011). This model is:

$$ECm = a\,ECa + c \quad \text{............(SLR)}$$

Where, a: regression coefficients; c is a constant

The treatment of this equation will be realized in two steps:

As a first step, it will be a question of looking for the validity of the equations A, B, C and D obtained by SLR model compared to the ECm measurements according to their respective sites.

As the second step, the equations A, B, C, D and G (equations obtained *ex situ* except for A) of the SLR model are applied to the site A (*in-situ*) to evaluate the ECc of the site A, which is considered as a reference site. This approach allows us to examine the possibility of using these calibration equations of ECa which are established *ex situ* (external calibration) to estimate the soil salinity *in situ*. This step is split into two phases:

First phase will be to determine the ECc of site A (*in situ*) by the equations A (*in situ*), B, C, D and G (*ex situ*) and to compare them statistically with the corresponding values of the ECm of site A;

Second phase will be to evaluate the precision of salinity maps according to the site A obtained with calibration equations B, C, D and G. To do this, 125 ECa measurements were systematically performed on the entire site A approximately at a lag distance of 20 m. The ECc are estimated by the introduction of ECa values of the site A, obtained by the EM38, in the equations A, B, C, D, and G of the selected regression model. This approach makes it possible subsequently to trace, by kriging the iso value maps of salinity for site A successively by equations A, B, C, D and G. Map units representing salinity classes ECc of Site A, obtained by the equation A, will be compared to those obtained by the equations B, C, D and G for the same site.

RESULTS AND DISCUSSION

Characteristics of studied soils: The main soil characteristics of the four studied sites are summarized in Table 1. The

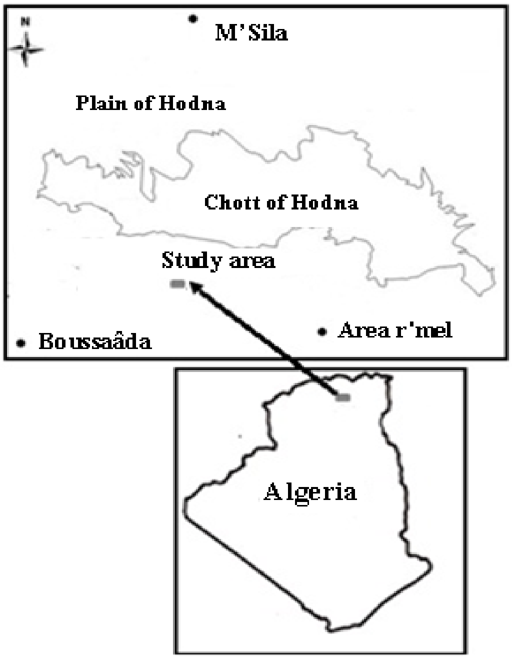

Fig. 1: Location of the studied zone.

Table 1: Average characteristics of soils studied.

	Site A	Site B	Site C	Site D	Total
$CaCO_3$ %	2.48 ± 1.31	6.39 ± 2.3	5.74 ± 1.71	3.55 ± 2.08	4.00 ± 2.32
Gypsum %	1.01 ± 0.84	7.72 ± 5.26	0.77 ± 1.1	4.76 ± 3	3.00 ±3.6
ECm dS/m	2.47 ± 2.02	2.17±0.81	0.52 ± 0.39	3.46 ± 1.96	2.21 ± 1.86
Sand %	77.15 ± 4.72	80.06 ± 3.19	87.65 ± 3.33	78.79 ± 6.93	80.00 ± 6.5
H %	21.99 ± 9.34	25.61 ± 6.95	15.29 ± 6.81	23.65 ± 12.2	21.42 ± 9.75
pH	8.39 ± 0.19	8.44 ± 0.17	8.67 ± 0.37	8.58 ± 0.20	8.52 ± 0.25

Table 2: The calibration equation parameter of the SLR model.

	Regression Equations	R^2
Equation A	ECm = 0.0109 ECa + 0.39	0.974***
Equation B	ECm = 0.008 ECa + 0.332	0.959***
Equation C	ECm = 0.0596 ECa - 2.192	0.820**
Equation D	ECm = 0.0126 ECa + 0.274	0.944***
Equation G	ECm = 0.012 ECa + 0.0196	0.903***

*, **,*** Significant at $P < 0.05$, $P < 0.01$, $P < 0.001$, respectively

Table 3: Descriptive statistics of ECm and ECc of SLR model.

	Electrical conductivity $dS.m^{-1}$			
	Minmum	Maximum	Mean	S-D
Site A				
Ecm	0.43	7.5	2.47	2
ECc (SLR)	0.47	6.98	2.29	1.8
Site B				
Ecm	1.09	3.23	2.17	0.81
ECc (SLR)	1.04	3.29	2.17	0.79
Site C				
Ecm	0.14	1.53	0.52	0.39
ECc (SLR)	0.23	1.47	0.56	0.35
Site D				
Ecm	0.15	5.44	3.46	1.96
ECc (SLR)	0. 49	5.59	3.3	1.81

calculated averages of all the samples indicate that the studied soil is sandy (≈ 80 % of sand), with a little bit $CaCO_3$ (≈ 4 %) and gypsum (≈ 3 %), alkali (pH ≈ 8.5), with low water content (≈ 21%) and salty (EC ≈ 2.2 dS/m). However, the results also show that these characteristics vary differently in space as indicated by the standard deviations for each of these parameters. In fact, the calculations reveal the presence of some differences between the studied sites. Thus, it appears that the average contents of $CaCO_3$ vary between 2.4% (site A) and 6.3% (Site B) and those of gypsum between 0.7% (Site C) and 7.7% (Site B). Soil water content vary between 15% (Site C) and 25% (Site B) and the ECm is between 0.52 dS/m (Site C) and 3.46 dS/m (Site D). Sand content is quite homogeneous and vary between 77% (Site A) and 87% (Site C). The pH, is relatively constant (8.39 <pH <8. 67). These results indicate the presence of slight differences in soil characteristics of all studied sites. Thus, it turns out that the site C is the least salty, with the least amount of gypsum and H%. It is also the most sandy and alkaline. While the site B, is the best endowed in $CaCO_3$, gypsum and H%. However, the standard deviations indicate that each of these parameters can vary more or less strongly within the same site.

Validation of calibration model: The parameters of calibration equations that relate ECm to ECa by SLR model are presented in Tables 2. The coefficients of determination R^2 for the five equations are statistically highly significant (p <0.01) with R^2 between 0.82 and 0.97 for SLR (Table 2). This result means that within the same site, ECm can be properly predicted by the SLR model.

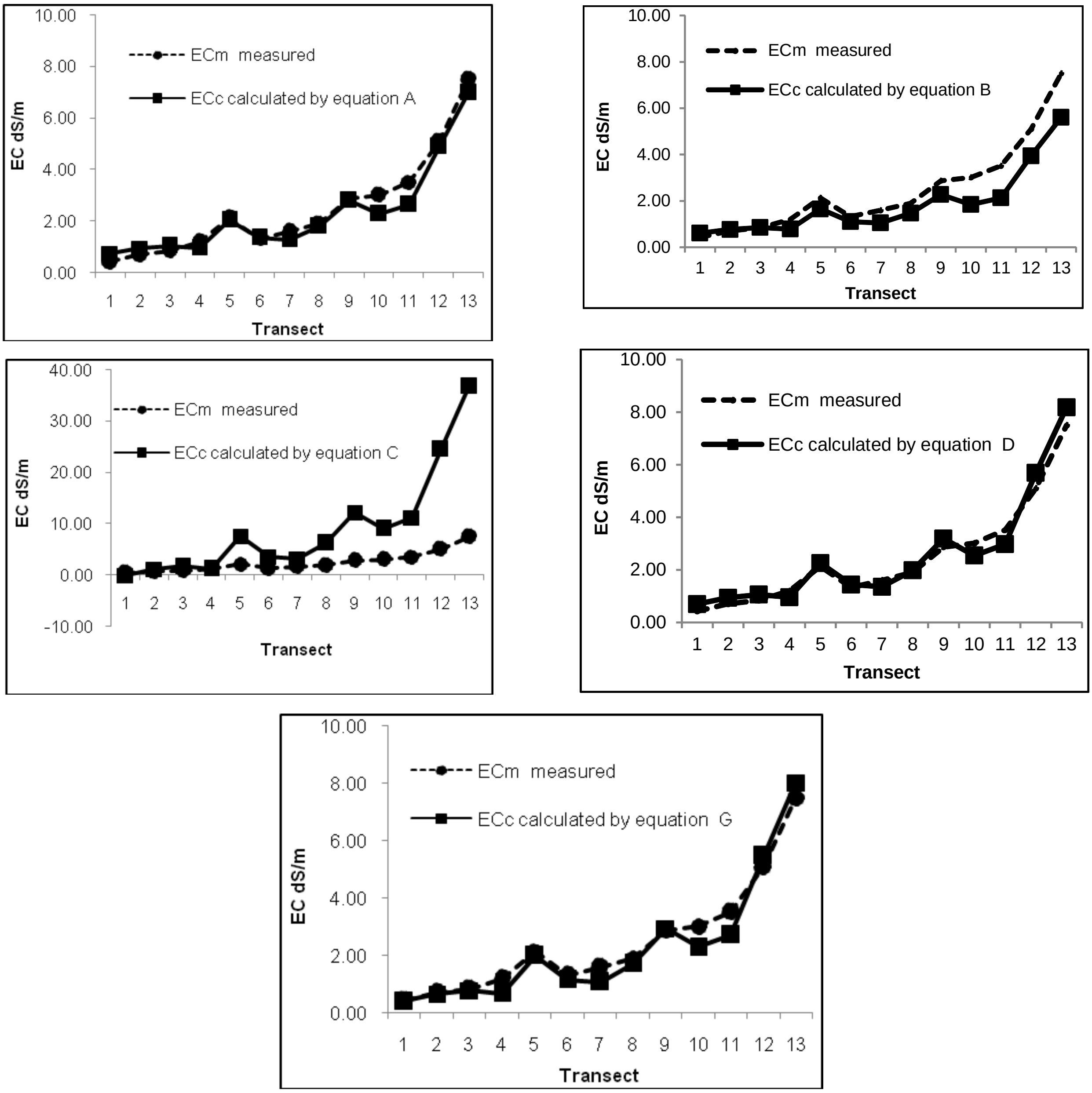

Fig. 2: Comparison between ECm measured in site A and the ECc calculated by the 5 equations of SLR model.

Moreover, the results (Table 3) show that the arithmetic means of ECc obtained by SLR model are comparable and similar to those of ECm, whatever the site is, suggesting that the SLR model estimate correctly the ECm values. Indeed, calculations (Table 4) show that the correlations made between ECm and ECc calculated by equations A, B, C and D of the SLR model are statistically highly significant ($0.9 < r < 0.999$; $p < 0.01$). Non-parametric tests of Sign and Wilcoxon (Table 5) confirm this result for sites A and D and indicate that the differences between the values of ECm and those of ECc calculated by the SLR model were not statistically significant. These differences are, however, differently appreciated in sites B and C. Similarly, this result confirms that, in the context of this study, the ECm can be properly estimated by ECa. Considering this result, and taking into account that the soils of the study area are sporadically and differently irrigated, which is reflected by a strong spatial and temporal variability of soil water content, the SLR model remains valid for predicting ECc from ECa data.

Table 4: Correlation between ECm and ECc of SLR models.

Site A	SiteB	Site C	Site D
r = 0.987***	r = 0.980***	r = 0.906**	r = 0.972***

, * Significant at $P < 0.01$, $P < 0.001$, respectively

Table 5: Wilcoxon and Sign tests between the ECm and ECc of SLR model.

Sites	Site A	Site B	Site C	Site D
Sign test	0.267	0.096	0.006*	0.267
Wilcoxon test	0.116	0.006*	0.003*	0.422

* Significant at $P < 0.05$

Table 6: Descriptive statistics of the absolute difference between ECc of SLR model and ECm.

Absolute difference (dS/m)	Minimum	Maximum	Mean	S-D
ECc(A_{eq})-ECm	0.04	0.88	0.3	0.26
ECc(B_{eq})-ECm	0.02	1.9	0.66	0.57
ECc(C_{eq})-ECm	0.03	29.25	6.7	8.6
ECc(D_{eq})-ECm	0.08	0.68	0.32	0.19
ECc(G_{eq})-ECm	0.02	0.79	0.32	0.27

eq: Equation

Table 7: Wilcoxon and Sign tests between the ECm of the site A and ECc of the SLR model in the Site A.

	Equation A	Equation B	Equation C	Equation D	Equation G
Sign test	0.267	0.096	0.006*	0.267	0.096
Wilcoxon test	0.116	0.006*	0.003*	0.422	0.08

*Significant at $P < 0.05$

Prediction of soil salinity by the SLR model in the site A: The ECc values from site A (reference site) obtained by A, B, C, D, and G equations of SLR model are illustrated in Fig. 2. This figure shows that the curves obtained by equations A, B, D and G are very close to the ECm curve, slightly lying above or below it. This result means that the ECm prediction using the four equations is reliable with a very slight over or under estimation. However, the curve obtained by the equation C seems to be relatively remote from ECm curve and appears to overestimate the EC values.

For a better evaluation of the prediction error, we calculated for each point in the site A, the absolute differences between ECc obtained by the five equations and the corresponding ECm. The results reported in Table 6 indicate the particularity of the equation C compared to the others. Indeed, the average difference between ECc calculated by C equation and corresponding ECm is 6.70 dS/m higher than the average value of ECm (2.47 dS/m) (Table 3). The average prediction error is about 271% [(ECc – ECm)/ECm) ×100]. The minimum and maximum absolute differences for this equation are between 0.03 dS/m and 29.25 dS/m (Table 6) which makes the prediction error comparing to minimum and maximum values of ECm (Table 3) vary between 6.98% [(0.03/0.43) × 100] and 390% [(29.25/7.5) × 100]. This result implies that this equation overestimates the ECm of site A and its use for salinity prediction in this site is not recommended. On the other hand, the average differences between ECm and ECc calculated by equations A, B, D and G vary between 0.3 dS/m and 0.66 dS/m (Table 6), which gives a prediction error between 12% and 26.7 %. For these equations, the minimum error is between 4.6% [(0.02/0.43) × 100] and 18% [(0.08/0.43) × 100] and the maximum error is between 9% [(0.68/7.5) × 100] and 25% [(0.88/7.5) × 100] depending on the used equation. Taking into account the extreme average values of the electrical conductivity (0.52 dS/m and 3.46 dS/m) (Table 1), absolute errors are between 0.02 dS/m (0.52*4.6)/100) and 0.16 dS/m (3.46*4.6)/100 for an error rate of 4.6% and between 0.13 dS/m (0.52*25)/100) and 0.87 dS/m (3.46*25)/100) for an error rate of 25%. These results mean, in the context of this

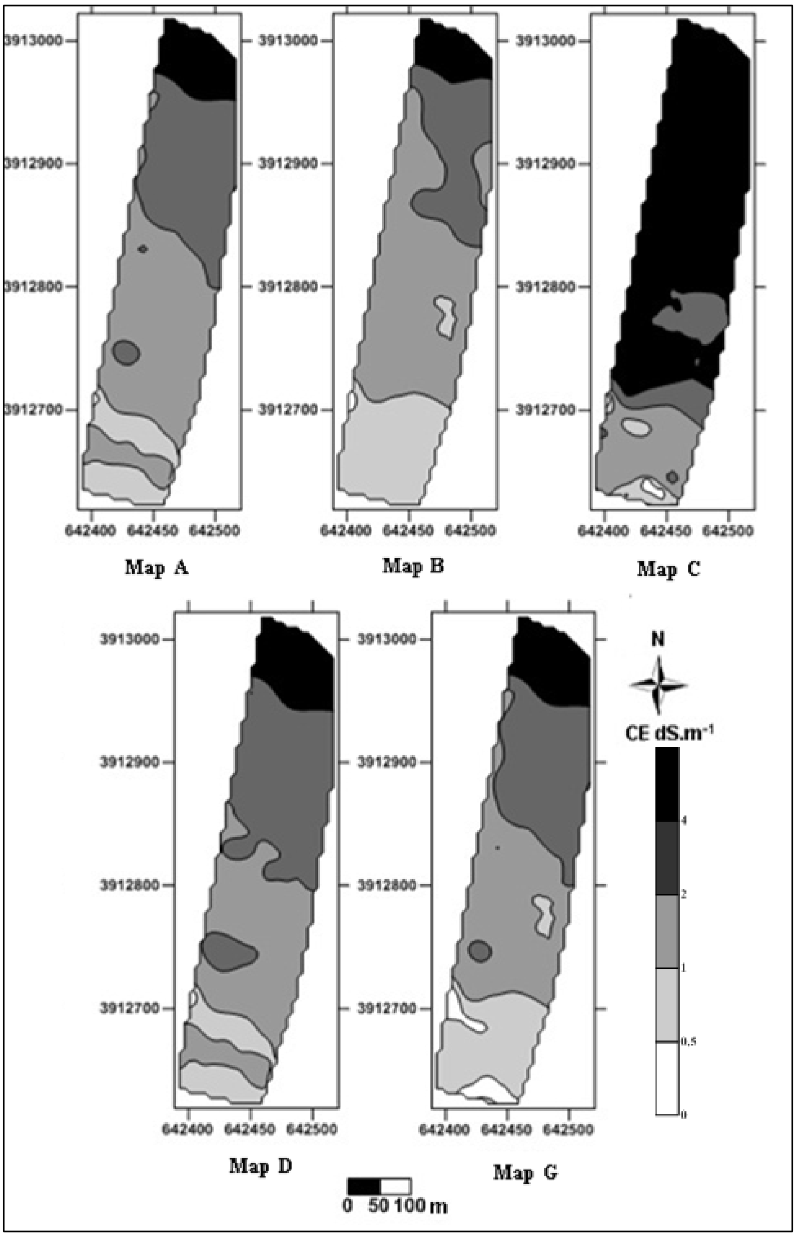

Fig. 3: Iso values salinity maps obtained in Site A with A, B, C, D and G equations of the SLR model.

study, that ECm = 3 dS/m, for example, is estimated between 3 ± 0.14 dS/m (error of 4.6%) and 3 ± 0.74 dS/m (error of 25%). Thus, one or more equations of SLR model can be used to predict EC in site A as confirmed by Sign and Wilcoxon tests (Table 7). Indeed, this table shows that the differences between ECm and ECc obtained by A, D, G equations (and with less accuracy by B) are statistically insignificant. Consequently, these equations give the best EC prediction in zone A. Table 7 confirms that C equation give the least accurate ECm prediction in this zone. However, the integration of Site C data in the overall equation G, does not affect the quality of the prediction.

Mapping the salinity by the SLR model in the site A: Soil salinity classes ECc are mapped by Kriging on the entire site A, using A, B, C, D and G equations of the SLR model. Salinity classes are determined according to standards established by Durand (1983).

The five iso value maps of ECc are shown in Fig. 3 and their characteristics in Table 8. The maps show a similarity

Table 8: Distribution of areas of the salinity classes in the whole maps A, B, C, D and G.

Salinity classes dS/m		0 - 0.5	0.5 - 1	1 - 2	2 - 4	>4
Map A	Area m^2	31.64	3427.99	13349.03	9390.04	3005.41
	Area %	0.11	11.74	45.71	32.15	10.29
Map B	Area m^2	79.94	6650.39	14323.96	6004.9	2144.92
	Area %	0.27	22.77	49.05	20.56	7.34
Map C	Area m^2	182.61	896.24	4442.48	3427.09	20255.7
	Area %	0.63	3.07	15.21	11.73	69.36
Map D	Area m^2	52.25	3198.73	11239.32	11186.65	3527.17
	Area %	0.18	10.95	38.49	38.31	12.08
Map G	Area m^2	1011.99	5726.63	10550.31	8596.49	3318.70
	Area %	3.47	19.61	36.13	29.44	11.36

Table 9: Error rate in the estimation of area of the maps B, C and D compared to the area in the map A.

Salinity classes dS/m	0 - 0.5	0.5 - 1	1 - 2	2 - 4	>4
Map B-A	0.16	11.03	3.34	-11.59	-2.95
Map C-A	0.52	-8.67	-30.50	-20.42	59.07
Map D-A	0.07	-0.79	-7.22	6.15	1.79
Map G-A	3.36	7.87	-9.58	-2.71	1.07

of the spatial distribution of salinity classes among the five maps. Indeed, they are all predicting salinity increase from south to north part of the area. However, in detail, there are differences between map A (reference map) and the others. Thus, it appears that map B, D and less accurately map G are the closest to map A, and map C is the farthest. Prediction differences quantify, for each salinity class, the estimation errors between map A and the others. Errors (expressed in percentage relative to the total area of site A) are calculated for each salinity class, considering the difference between the area predicted by equation A and the area predicted by the other equations (Table 9). Analysis of Table 9 reveals that the predicted areas are differently overestimated (0.07% to 59.07%) or underestimated (-30.50% to -0.79%) according to the equation used and the salinity class considered. The less salty class "ECm < 0.5 dS/m" is the best estimated (error <3.36%) compared to other classes, due probably to its very small area which represents only 0.11 % of the total area of the map A (Table 8).

Furthermore, it is apparent that the equation C grossly overestimates (59%) the area of the class "EC > 4 dS/m" to the detriment of the other classes "2-4 dS/m" (-20%), "1-2 dS/m" (-30%) and "0.5-1dS/m" (-8%).

This result suggests that the equation C has lower accuracy than the other equations for predicting salinity distribution in site A. This may be due to the fact that site C is less salty, less humid and more sandy than site A. However, the maximum relative error given by the other equations is only about 11% at most.

CONCLUSION

This study showed that the SLR model predicts correctly the ECm values in the site in which it was established. Therefore, in this kind of environment, the SLR model is sufficient to predict correctly the soil salinity. This study also showed that the differences between ECc calculated by different SLR equations developed *ex situ*, and the *in situ* ECm measurements are all statistically insignificant except for equation C. Therefore, apart from the equation C (Site C is more sandy, less salty and drier than the rest of the sites), the use of SLR equations for predicting the *ex situ* salinity is possible and the obtained results are satisfactory. Furthermore, calculations showed that the integration of Site C data in the overall equation G does not alter the quality of the salinity prediction.

The results also showed that the iso value maps of salinity produced by kriging using the SLR equations elaborate *ex situ* are, with few detail meadows, similar to that achieved by SLR equation developed *in situ*. Indeed, all the maps are predicting the increase in soil salinity from the south to the north of the area. However, according to the equation used, the prediction error with respect to the *in situ* equation is quite variable. Thus, the calculations showed that this error remains generally insignificant and acceptable (absolute error between 0.07% and 11%) except for the C equation where it can reach 59%.

Finally, all of these results suggest that the calibration equations obtained by SLR model in a small area can be generalized to wider areas, provided that the soil environment remains fairly homogeneous, although soil humidity varies in space.

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